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ScienceDirect

Energy Procedia 63 (2014) 2663 – 2682

Energy Procedia

GHGT-12

Which reservoir for low cost capture, transportation, and storage?

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Abstract

Quality and location of a carbon dioxide (CO_2) storage reservoir are critical for low cost carbon capture and storage (CCS). This analysis models the combination of capture, transportation, and storage costs to estimate a total cost of CCS. Cost of capture at the source is available for annual rates between 4.1 and 0.7 million tonnes of CO_2. Cost of transportation is modeled for the distance between the source and the storage reservoir. Cost of CO_2 storage is modeled for four representative reservoirs, two Rose Run and two Mt Simon reservoirs, each reservoir in a dome or regional dip structural setting.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CCS, capture cost, transportation cost, storage cost, Mt Simon, Rose Run

1. Introduction

Over the last three years, the U.S. Department of Energy's Office of Fossil Energy (FE) has funded the National Energy Technology Laboratory (NETL) to develop a model, the FE/NETL CO_2 Saline Storage Cost Model, that estimates the cost of long-term CO_2 storage in saline aquifers [1]. This cost model and another model developed to assess the cost of transporting CO_2 from source to sink, the FE/NETL CO_2 Transport Cost Model [2], have found useful applications in support of NETL's efforts in modeling the costs associated with carbon capture and storage

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.289

(CCS). For example, these two models were used to model storage in four sedimentary basins (Illinois, Williston, Powder River, and East Texas), including transportation over a distance of 100 kilometers (62 mi), the results of which are reported in the Quality Guidelines for Energy System Studies report on Carbon Dioxide Transport and Storage in NETL Studies, commonly referred to as the Four Basin Study [3].

This report presents initial work to combine the modeling capabilities of the FE/NETL CO_2 Saline Storage Cost Model v2.0 and the FE/NETL CO_2 Transport Cost Model with the cost of capture to estimate an all-inclusive cost for capture, transportation, and storage. Capture costs were not modeled for this study but are based on NETL's publication *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity* [4]. In the year since the work was done for this study, the cost model and geologic database have been updated and are now posted to the NETL website [1]. The geologic database was also updated per the current National Carbon Sequestration Database and Geographic Information System (NATCARB) database. The purpose of this paper is to report on a methodology for modeling storage costs and transportation costs in combination with capture costs across a range of capture rates and range of reservoir quality to provide an overall cost of CCS.

The estimated cost of CCS will vary with the amount of emissions captured at a source, the transport distance between source and storage reservoir, and the quality of the storage reservoir. At a specific rate of capture, the cost of capture and the cost of storage are fixed, and the variable impacting the cost of CCS is the distance of transportation. If the rate of capture and the cost of capture and cost of storage change, then consideration of the distance of transportation changes. This study looks at a change in the location of a source, which changes transportation distance, as well as a change in the rate of capture, which impacts the cost of storage and cost of transportation. Results from this analysis can be used to determine where a source along the Ohio River valley might find suitable storage considering the quality of the potential storage reservoir and the transportation distance. Capture, transportation, and storage occur over a 30-year period.

2. Representative Storage Reservoirs

The source of CO_2 in this study is hypothetical and location of the storage reservoir is representative. Location of the source is proximal to the Rose Run 3 and Rose Run 4 reservoirs. There are two other, more distal, reservoirs in this study that the source can choose for storage, the Mt Simon 1 and Mt Simon 9. These four representative reservoirs are from the geologic database within the FE/NETL CO_2 Saline Storage Cost Model and were selected as they provide both a range of quality (Table 1) for storage as well as a general east-to-west alignment from the Appalachian Basin to the Illinois Basin, an area that can provide storage potential for sources along the Ohio River valley. The Mt Simon formation is subdivided into nine reservoirs whose individual centroids are located in Illinois, Michigan, Ohio, and Kentucky. The Mt Simon 9 reservoir is located on the Findley Arch in western Ohio (Figure 1). The Mt Simon 1 reservoir is in the Illinois Basin in central Illinois. The Rose Run formation is subdivided into five reservoirs whose individual centroids are located in Pennsylvania, West Virginia, Kentucky, and Ohio. The Rose Run 3 reservoir is located in west central Pennsylvania and the Rose Run 4 reservoir is located in northwestern Pennsylvania. Figure 1 shows the geographic locations of the Rose Run and Mt Simon reservoirs modeled, the location of the source relative to both Rose Run 3 and Rose Run 4 reservoirs and the pipelines connecting the source with its storage. As noted above, the location for each of the reservoirs modeled is representative; it is the latitude and longitude for the centroid of the area represented by each reservoir in the geologic database for the FE/NETL CO_2 Saline Storage Cost Model v2.0.

Table 1. Reservoir storage parameters for reservoirs modeled.

Reservoir Parameter	Rose Run 3	Rose Run 4	Mt Simon 9	Mt Simon 1
Depth - m	4,267	1,981	1,219	1,219
Thickness - m	137	38	46	305
Porosity - %	8.0	8.0	14.0	12.0
Permeability - md	3.0	4.0	50.0	100.0
Storage Efficiency %- Dome	16.97	16.97	15.28	15.28
Storage Efficiency % - Reg Dip	4.71	4.71	5.63	5.63

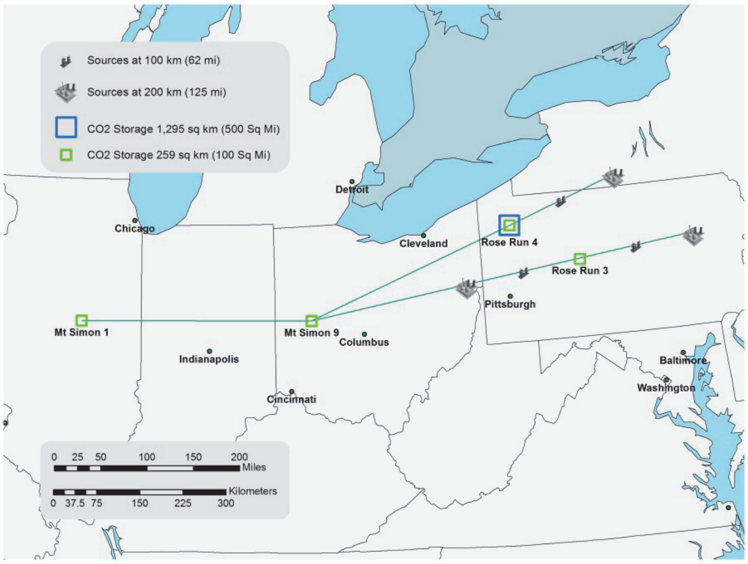

Figure 1: Map location of Rose Run and Mt Simon reservoirs modeled and route of pipeline connecting source with storage.

The reservoirs shown in Figure 1 were selected because they present a range in reservoir quality. Table 1 displays the characteristics of each reservoir including height, porosity, storage coefficient, and permeability. The Mt Simon reservoirs are shallower than both Rose Run reservoirs, which has an impact on drilling and operational cost of injection wells and monitoring wells. Reservoir thickness and permeability impact injectivity and, in turn, impact the number of injection wells needed to store the annual mass of captured CO_2 delivered to a storage site. Reservoir thickness and porosity along with the storage coefficient determine the volume of storage for a particular reservoir that may accommodate the injected mass of CO_2 to be stored as well as the areal extent of the CO_2 plume. The areal extent of the CO_2 plume is a critical cost driver for monitoring costs, especially with respect to monitoring wells and seismic data acquisition. The Mt Simon 1 is the best overall reservoir with respect to formation height, permeability, and porosity. Both Rose Run reservoirs have poor permeability, though their porosity is adequate. The Rose Run 4 is the poorest quality reservoir. The range of storage costs resulting from the range in storage quality provides for possible trade-offs in quality and proximity to the source while selecting a cost effective storage reservoir.

3. Capture Costs

Capture costs are for newly built supercritical pulverized coal plants. Costs used for the analyses in this paper are based on Case 12 of NETL's Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity [4]. Plant capacity factor is 85 percent with 90 percent of the CO_2 stream captured. Modeled CO_2 captured was rounded to one decimal place. As shown in Table 1, economies of scale are exhibited since the cost of capture decreases as the mass of CO_2 captured increases.

Table 2. Source parameters – power plant output, annual mass of CO_2 captured, and cost of capture.

Gross Output - MW	663	581	482	362	241	121
Net Output - MW	550	482	400	300	200	100
CO_2 Captured - Mt/yr	4.1	3.6	3.0	2.2	1.5	0.7
Cost of CO_2 Captured - $/tonne	56.10	57.80	60.20	64.30	70.60	83.40

4. Modeling Transport Costs

Previous editions of the Four Basin Study used an early form of CO_2 transportation cost model that was significantly modified during 2013 to become the FE/NETL CO_2 Transport Cost Model. This model is designed to estimate the cost of pipeline transport of CO_2 from a source to a long-term storage location. Using Excel-based deterministic modeling, the model estimates a first-year, break-even cost (price per tonne to transport) based on a number of parameters, the most important of which are the annual mass of CO_2 transported and distance of transport. The reader is referred to the FE/NETL CO_2 Transport Cost Model User's Manual for additional details [4].

The cost to transport captured CO_2 over various distances was modeled to connect the hypothetical source in its various locations to potential storage at one of the four representative reservoirs. Figure 2 displays the resulting transportation costs for sources considering the Rose Run 4, Rose Run 3, Mt Simon 1, and Mt Simon 9 reservoirs. These representative results show that there are economies of scale in transporting captured CO_2 by pipeline. A distance of 100 or 200 kilometers will connect the source to either of the Rose Run reservoirs. Longer distances will connect the source to either Mt Simon reservoir. As distance increases between the CO_2 source and a storage site, more CO_2 will need to be shipped to keep unit costs down. Higher transportation costs will require lower storage costs to keep the combination economic.

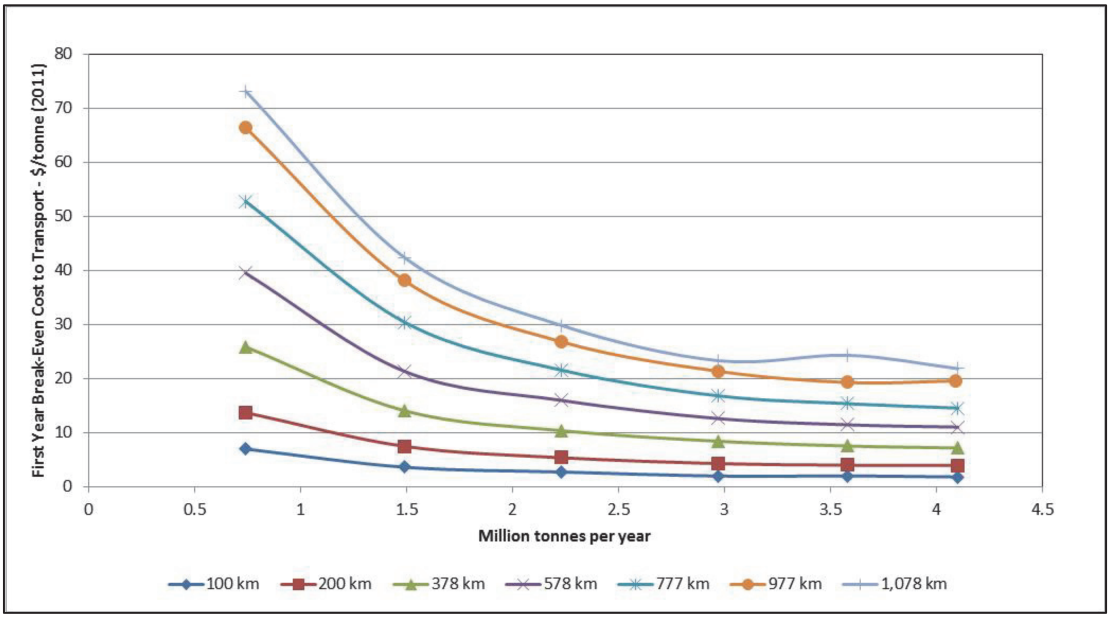

Figure 2. Economies of scale for pipeline transportation for sources considering Rose Run 3, Rose Run 4, Mt Simon 9, or Mt Simon 1 storage

5. Modeling Storage Costs

The FE/NETL CO_2 Saline Storage Model v2.0 was used to generate storage costs for this analysis. The standard baseline case scenario for CO_2 saline storage cost modeling that is used in the analyses is described is some detail in FE/NETL CO_2 Saline Storage Cost Model: Model Description and Baseline Results [3].

The cost model allows for storage of the entire amount of CO_2 injected over a 30-year period of operations. The mass of CO_2 that can be stored in a reservoir is defined by the equation:

$$G_{CO2} = Ah\rho_{CO2}\Phi E \quad (1)$$

The mass of CO_2 stored (G_{CO2}) equals the product of the area (A) of the reservoir, the height (h) of the reservoir, the density ($\boldsymbol{\rho}_{CO2}$) of the stored CO_2 at reservoir conditions, the porosity of the reservoir rock, and the storage coefficient (E) for the reservoir rock. This is the equation used in the FE/NETL CO_2 Saline Storage Cost Model. Solving for area (A):

$$A = G_{CO2}/h\rho_{CO2}\Phi E \quad (2)$$

Reservoir height, porosity, and storage coefficient are inversely proportional to area occupied by the injected CO_2.

The reservoirs modeled in this study are found in the geologic database included in the FE/NETL CO_2 Saline Storage Cost Model v2.0. The areal extent for each reservoir is posted in this database and is described in the User's Manual [5] as well as in the Model Description and Baseline Results for the Saline Storage Cost Model [6]. Based on work done by USGS [7], the percentage of a reservoir's areal extent assigned to either a dome or anticline structure is 1.25 percent each and the regional dip structural setting represents the remaining 97.5 percent of the reservoir.

Table 3. Mass of annual CO2 injected and total mass injected over 30 years with resulting plume size for reservoirs modeled.

Annual mass CO_2 injected - Mt	4.1	3.6	3.0	2.2	1.5	0.7
Total mass CO_2 stored - Mt	123	108	90	66	45	21
Rose Run 4						
Dome structure = 291 km^2						
Dome storage cost - \$/tonne	na	na	na	40.93	41.33	46.76
Plume Area - km^2	na	na	na	167	128	60
Uncertainty Area -km^2	na	na	na	291	224	104
Regional Dip structure = 22,727 km^2						
Reg Dip storage cost - \$/tonne	83.91	83.74	83.76	84.53	85.18	91.58
Plume Area - km^2	1,259	1,105	921	675	305	215
Uncertainty Area -km^2	2,203	1,934	1,612	1,182	806	376
Rose Run 3						
Dome structure = 422 km^2						
Dome storage cost - \$/tonne	18.65	19.29	19.95	22.03	24.96	35.80
Plume Area - km^2	91	80	66	49	33	15
Uncertainty Area -km^2	159	139	116	85	58	27
Regional Dip structure = 33,670 km^2						
Reg Dip storage cost - \$/tonne	34.41	35.16	36.04	38.21	42.34	55.25
Plume Area - km^2	327	287	239	175	120	56
Uncertainty Area -km^2	572	502	418	307	209	98
Mt. Simon 9						
Dome structure = 787 km^2						
Dome storage cost - \$/tonne	13.19	13.43	13.63	14.26	15.40	19.21
Plume Area - km^2	199	175	145	107	73	34
Uncertainty Area -km^2	348	305	254	187	127	59
Regional Dip structure = 61,365 km^2						
Reg Dip storage cost - \$/tonne	27.60	27.94	28.09	28.73	30.20	34.69
Plume Area - km^2	539	474	395	290	197	92
Uncertainty Area -km^2	944	829	691	507	346	161
Mt. Simon 1						
Dome structure = 878 km^2						
Dome storage cost - \$/tonne	5.32	5.66	5.93	6.81	8.34	13.93
Plume Area - km^2	34	30	25	18	12	6
Uncertainty Area -km^2	60	52	44	32	22	10
Regional Dip structure = 68,436 km^2						
Reg Dip storage cost - \$/tonne	8.20	8.49	8.82	9.82	11.41	16.86
Plume Area - km^2	93	81	68	50	34	16
Uncertainty Area -km^2	162	142	119	87	59	28

The minimal criteria for siting a CO_2 storage field is the demonstration that the proposed storage reservoirs have '…sufficient areal extent, thickness, porosity, and permeability to receive the total anticipated volume of the carbon dioxide stream.' [40 CFR 146.83(a)(1)] Finding suitable storage is a critical challenge for potential captured CO_2 storage operators. A review of the data for the Mt Simon 9 and Rose Run 3 reservoirs suggests that one source, unless it is a small source, may have to utilize multiple reservoirs. Some level of knowledge of this potential storage capacity will be defined by site characterization and continue to be proven up through injection operations. The storage operator will continue to learn more about their storage reservoir during operations but will not know exactly what the reservoir will hold until injection operations are done and the injection well is plugged.

In the baseline scenario for the FE/NETL CO_2 Saline Storage Cost Model an areal limit of 259 square kilometers (100 mi^2) is applied to the plume uncertainty boundary. This areal limit reflects some concerns regarding the ability to secure pore space rights over a larger area as well as potential anthropogenic restrictions at the surface. Each storage reservoir plotted on the map in Figure 1 is defined by a 259 square kilometers (100 mi^2) square. This areal limit on the plume uncertainty boundary is not enforced in the analyses within this report, so storage costs reflect the same rate of annual injection and the same mass of CO_2 stored over 30 years of operations. However, the areal limit does provide a reference on the areal extent a CO_2 plume can reach or exceed and is an important consideration in selecting a potential storage site.

The Rose Run 4 reservoir provides a good example. In the FE/NETL CO_2 Saline Storage Cost Model, dome and anticline structural settings each represent 1.25 percent of the entire areal extent of a reservoir's surface area. The areal extent for the Rose Run 4 dome structure is only 291 square kilometers (112.5 mi^2); the same areal extent has the plume uncertainty boundary for 66 million tonnes of CO_2 injected at a rate of 2.2 million tonnes over 30 years (Table 2). The areal extent of the dome structure for the Rose Run 4 is too small to accommodate the larger rates of injection for the 30 years of operations modeled. For these higher rates of injection and larger mass of CO_2 to be stored, the operator would have to find another reservoir with sufficient potential to accommodate larger sources or multiple reservoirs. For the Rose Run 4 regional dip structural setting, there is more than sufficient storage capacity for a single project, but the areal extent of the plume's uncertainty boundary is more than 259 square kilometers (100 mi^2) for all rates of injection modeled. A 1,295 square kilometer (500 mi^2) box is also posted on the map in

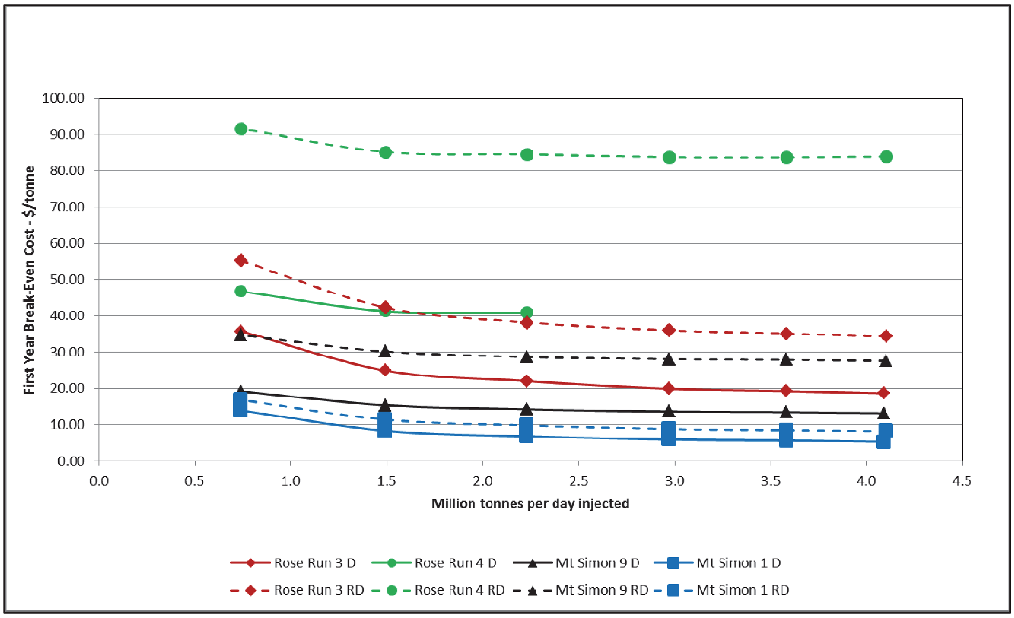

Figure 3. Economies of scale of storage cost for reservoirs modeled. The cost curve for the dome structure for the Rose Run 4 reservoir ends at 2.2 Mt of CO2 because the structure does not have the areal extent needed to accommodate a larger mass of CO2.

Figure 1 for the Rose Run 4 reservoir. Modeling an annual injection rate of 4.1 Mt for the Rose Run 4 reservoir in a regional dip structure setting calculates a storage cost of $83.91 per tonne for all 123 Mt of CO_2 injected over 30 years, creating a CO_2 plume uncertainty area covering 2,203 km^2 (850 mi^2). Limiting the areal extent of the plume uncertainty boundary to 259 square kilometers (100 mi^2) restricts injection to 0.48 Mt per year with only 14.5 Mt of CO_2 stored at a cost of $98.37 per tonne. For either structural setting modeled here, the Rose Run 4 reservoir cannot provide a suitable reservoir and keep the plume within the boundary limits of the baseline scenario.

The Mt Simon 1 reservoir as the best combination of reservoir parameters for the reservoirs modeled. It also has the largest areal extent for dome (878 km^2) and regional dip (68,436 km^2) structural settings, which provides it with sufficient volume for both structural settings to accommodate the mass of CO_2 modeled over 30 years of injection. The dome structural setting for the Rose Run 3, in combination with good reservoir height, is sufficient, but the regional dip structural setting results in plume areas that will exceed the 259 square kilometers plume uncertainty limit. For the Mt Simon 9 reservoir, the areal extent of CO_2 plumes at the higher masses of CO_2 injected for dome structures exceed the 259 square kilometers limit while for the regional dip structural setting, only the lowest injection rate stays within the 259 square kilometers limit. These are limits that will have to be taken into consideration when developing a potential CO_2 storage site.

Figure 3 illustrates an economy of scale for storage in each of the reservoirs modeled. Storage costs are lowest for the Mt Simon 1 reservoir, a dome structural setting plotted just below the Mt Simon regional dip structural setting. The high cost reservoir is the Rose Run 4 regional dip structural setting. Due to volumetric limitations, cost data for the Rose Run 4 dome structural setting is limited to annual injection rates of 2.2 Mt/yr and lower. Storage costs illustrated in Figure 3 are combined with the transportation costs illustrated in Figure 2 and discussed in the following section. A low cost combination of storage and transportation in addition to the cost of capture will provide a low cost combination for CCS.

6. Analysis

NETL set out to perform a simple analysis of the full cost of carbon capture, transportation, and storage and the resulting impacts on reservoir selection. The combination of data on capture costs with transportation and storage cost modeling provides a methodology for the selection of cost effective storage for sources capturing different masses of CO_2. Results from this analysis are then used to determine where hypothetical sources might find suitable storage considering the quality of the potential storage reservoirs and the transportation distance. This section describes the test matrix design and details the results of the test matrix analysis.

6.1. Test Matrix Design

To study a variety of storage scenarios that might arise for the representative storage reservoirs in a systematic manner, a simple test matrix was designed that represents various combinations of important parameters to be tested including the location of the CO_2 source and the rate of CO_2 capture at the source. The components of the test matrix are source location, either 100 km or 200 km from a Rose Run reservoir, annual rate of CO_2 captured at the source (with associated cost), the transportation distance between source and storage site for each rate of CO_2 captured (with associated costs), and finally the cost of storage of each rate of CO_2 captured, all which sum to a total cost for CCS. Test matrix results and graph are illustrated for each source location (Figure 4 and Table 4, for example).

The location of the CO_2 source determines the transport distance to affordable storage. The source does not have a specific latitude-longitude location. Its location is associated with a fixed transport distance from the Rose Run reservoirs. The initial transport distance modeled is 100 kilometers (62 mi) from the source to either the Rose Run 3 or Rose Run 4 reservoir. This is the standard distance modeled in the Four Basin Study. The next distance modeled is 200 kilometers (125 mi) to either Rose Run reservoir. Other distances modeled connect the source to either of the Mt Simon reservoirs.

All pipeline distances go to or through the storage reservoir centroids to the destination reservoir as shown in Figure 1. For all scenarios modeled, the source is east of the Rose Run 3 or Rose Run 4 storage reservoir or west of the Rose Run 3 reservoir at a distance of 100 or 200 kilometers. If the source is east of either Rose Run reservoir, the pipeline goes through that Rose Run centroid location westward to the Mt Simon 9 or continues through the Mt Simon 9 centroid to the Mt Simon 1 location. If the source is west of the Rose Run 3, then the pipeline simply goes east to the Rose Run 3 or west to the Mt Simon 9 or Mt Simon 1 reservoir in a similar manner. The resulting pipeline distances modeled are as follows in kilometers (miles): 100 (62), 200 (125), 277 (172), 378 (235), 481 (299), 578 (359), 583 (362), 676 (420), 679 (422), 777 (483), 880 (547), 977 (607), 982 (610), and 1,078 (670). For all distances modeled, the pipeline is a dedicated line connecting a single source with a single storage reservoir.

Costs of capture, transport, and storage, as well as reservoir selection, will all depend on the rate at which CO_2 is produced and captured at the source. This rate determines the specific mass of CO_2 that the source has to store over a period of time, which in turn is defined by the qualities that are necessary in a potential storage site or sites. Component costs for capture, transport, and storage are modeled for the following annual rates of capture: 4.1 million tonnes (Mt), 3.6 Mt, 3.0 Mt, 2.2 Mt, 1.5 Mt, and 0.7 Mt. Power plant output for the range of CO_2 captured ranges from 550 MW_{net} (663 MW_{gross}) for 4.1 Mt/yr of CO_2 emissions captured to 100 MW_{net} (121 MW_{gross}) for 0.7 Mt/yr of CO_2 emissions captured (see Table 1).

6.2. Test Matrix Model Run Results

For each scenario in the test matrix, data on the cost of capture is combined with the modeled costs of transport and storage to calculate a total CCS cost. These costs can then be used to compare the four representative reservoirs as potential sites for CO_2 storage and determine which reservoir would be selected in each scenario. The optimal choice for the source is the reservoir with the lowest total CCS cost. While the Mt Simon 1 reservoir has the best reservoir qualities and is shown to have the lowest storage costs for each of the CO_2 capture rates modeled, it is also the furthest away from the potential source locations modeled. In some cases, the cost disadvantage of storage in the closer Rose Run reservoirs provides a positive cost differential that justifies longer transportation distances. The Rose Run 4 or Rose Run 3 reservoirs are the primary reservoirs considered for storage by the source, if total CCS costs are lower than either Mt Simon reservoir. At a distance of 100 km or 200 km the source is always closer to either Rose Run reservoir. Discussion of modeling results is organized per each Rose Run reservoir.

6.2.1. Rose Run 4 Reservoir

The Rose Run 4 reservoir was the thinnest of the four reservoirs modeled. Height or thickness of the reservoir is critical for both injection and storage and, therefore, cost of storage. The reservoir height in the Rose Run 4 is about a quarter of that in the Rose Run 3 (Table 1), while porosity and permeability are the same for both reservoirs. With only 38 meters (125 ft) of reservoir height, the areal extent of the CO_2 plume in the Rose Run 4 reservoir is considerably larger than the areal extent of the same sized plume in the other reservoirs (see Table 2).

Table 4 shows the results for capture cost, storage cost, transportation cost, and overall CCS cost in the Rose Run 4, Mt Simon 1 and Mt Simon 9 reservoirs (dome and regional dip) at all rates of capture for a source located 100 kilometers (62 mi) east of the Rose Run 4 reservoir. In a dome structural setting, storage costs for the Mt Simon 1 reservoir are the lowest (30 to 60 percent lower than the cost to store in the Mt Simon 9 reservoir) but the overall CCS costs are lower for the Mt Simon 9 reservoir due to the shorter transport distance and lower transportation costs for the modeled rates of capture. However, if it is a challenge to secure sufficient acreage to cover the necessary pore space rights within the Mt Simon 9 reservoir at larger capture rates, Mt Simon 1 can also be utilized since the Mt Simon 1 is only about a $1.00 per tonne more expensive than Mt Simon 9 for rates of capture at or above 3.0 Mt. Except as an alternative storage site at the 0.7 Mt capture rate, the high cost of storage in the Rose Run 4 reservoir precludes its use at all rates of capture. Even on-site storage in the Rose Run 4 reservoir is unlikely due to the large areal extent of the plume, which in turn drives costs. The CCS cost curve for the dome structure for the Rose Run 4 reservoir (Figure 4) ends at 2.2 Mt of CO_2 because the structure does not have the areal extent needed to accommodate a larger mass of CO_2.

For the regional dip structural setting, the Mt Simon 1 reservoir offers the lowest overall cost of CCS for all but the lowest rate of capture. In this structural setting, Mt Simon 1 storage costs are 50 to 70 percent lower than the cost to store in the Mt Simon 9, which more than offsets the higher transport costs due to the increased distance from the source. At the lowest capture rate of 0.7 Mt per year, the Mt Simon 9 reservoir is the low-cost storage site. Although there is no constraint on the areal extent of the plume in these analyses, it can be noted that the areal extent of the CO_2 plume for the Mt Simon 1 dome and regional dip structural settings is well within the 259 square kilometer (100 mi^2) uncertainty limit for all rates of capture. Figure 4 shows these cost trends for each of the reservoirs and both structural settings.

The cost advantage of the Mt Simon 1 reservoir in a regional dip structural setting is due to the change in storage coefficients. For a dome structural setting, the storage coefficient is 15.28 percent, whereas in the regional dip

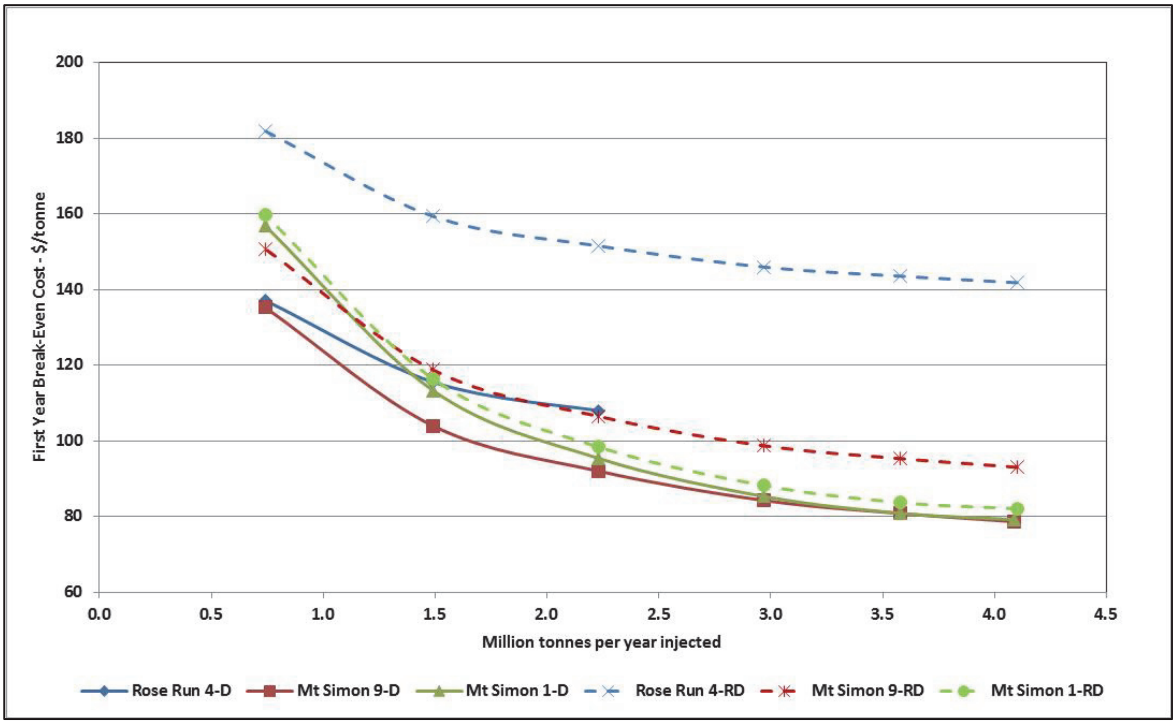

Figure 4. Cost for CCS for a source located 100 kilometers (62 mi) east of the Rose Run 4 reservoir. D = Dome and RD = Regional Dip.

Table 4. Cost of CCS for a source located 100 kilometers (62 mi) east of the Rose Run 4 reservoir.

Plant MW	Captured CO2 Mt/y	Capture Cost New Build $/tonne	Rose Run 4 Trans 100 km	Rose Run 4 Storage	Rose Run 4 Trans+Stor	Rose Run 4 CCS	Mt Simon 9 Trans 481 km	Mt Simon 9 Storage	Mt Simon 9 Trans+Stor	Mt Simon 9 CCS	Mt Simon 1 Trans 880 km	Mt Simon 1 Storage	Mt Simon 1 Trans+Stor	Mt Simon 1 CCS
Dome Structure														
663/550	4.1	56.10					9.33	13.19	22.52	**78.62**	17.75	5.32	23.07	**79.17**
581/482	3.6	57.80		Structure too small			9.57	13.43	23.00	**80.80**	17.39	5.66	23.05	**80.85**
482/400	3.0	60.20					10.41	13.63	24.04	**84.24**	19.16	5.93	25.09	**85.29**
362/300	2.2	64.30	2.74	40.93	43.67	107.97	13.45	14.26	27.71	**92.01**	24.28	6.81	31.09	95.39
241/200	1.5	70.60	3.63	41.33	44.96	115.56	17.98	15.40	33.38	**103.98**	34.39	8.34	42.73	113.33
121/100	0.7	83.40	7.00	46.76	53.76	137.16	32.71	19.21	51.92	**135.32**	59.61	13.93	73.54	156.94
Regional Dip Structure														
663/550	4.1	56.10	1.83	83.91	85.74	141.84	9.33	27.60	36.93	93.03	17.75	8.20	25.95	**82.05**
581/482	3.6	57.80	2.03	83.74	85.77	143.57	9.57	27.94	37.51	95.31	17.39	8.49	25.88	**83.68**
482/400	3.0	60.20	2.01	83.76	85.77	145.97	10.41	28.09	38.50	98.70	19.16	8.82	27.98	**88.18**
362/300	2.2	64.30	2.74	84.53	87.27	151.57	13.45	28.73	42.18	106.48	24.28	9.82	34.10	**98.40**
241/200	1.5	70.60	3.63	85.18	88.81	159.41	17.98	30.20	48.18	118.78	34.39	11.41	45.80	**116.40**
121/100	0.7	83.40	7.00	91.58	98.58	181.98	32.71	34.69	67.40	**150.80**	59.61	16.86	76.47	159.87

structural setting, the storage coefficient is 5.63 percent. While the Mt Simon 1 and Mt Simon 9 reservoirs have identical values for porosity and storage coefficient, the Mt Simon 1 reservoir is 259 meters (850 ft) thicker. In a dome structural setting, this difference in reservoir height does not work against the cost of storage of the Mt Simon 9 reservoir relative to storage costs for the Mt Simon 1 reservoir with respect to transportation distance. In consideration of using a reservoir in the regional dip structural setting, storage costs for the Mt Simon 9 reservoir across the range of mass of CO2 modeled increase between 81 (0.7 Mt CO2 captured) and 109 percent (4.1 Mt CO2 captured) over those for a dome structural setting. For the Mt Simon 1 reservoir, these storage costs have a smaller increase, between 21 and 54 percent. The thicker reservoir has a distinct advantage when storage capacity becomes restricted due to other parameters and it becomes cost effective to transport the extra 399 kilometers (248 mi).

Table 5 displays similar results for a source located 200 kilometers (125 mi) east of the Rose Run 4 reservoir. For the dome structural setting, either the Mt Simon 1 or Mt Simon 9 can provide low-cost storage at capture rates from 4.1 to 3.0 Mt per year; overall CCS prices are within $1.05 at each of these rates of capture. At lower capture rates, the Mt Simon 9 is the low cost storage reservoir. Results are also similar to the previous scenario for the regional dip structural setting. Once again, the Mt Simon 1 reservoir offers the lowest overall cost of CCS for all but the lowest rate of capture. At the lowest capture rate of 0.7 Mt per year, the Mt Simon 9 reservoir is the low-cost storage site. Figure 5 shows these cost trends for each of the reservoirs and both structural settings.

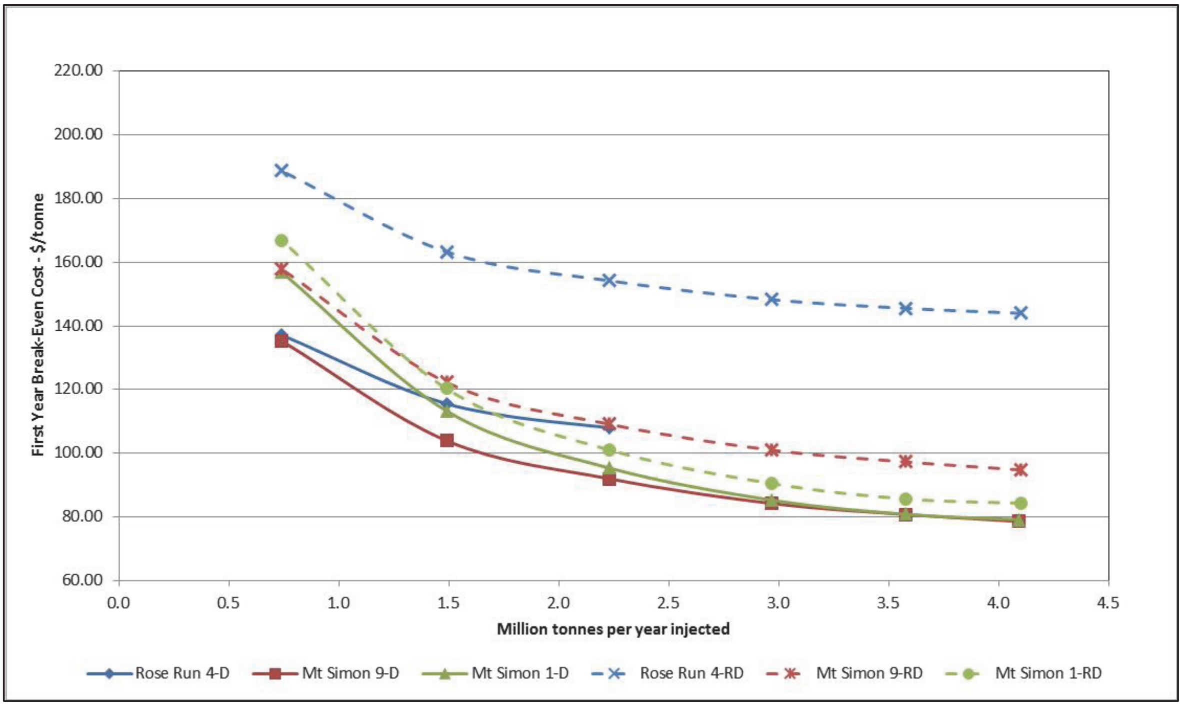

Figure 5. Cost for CCS for a source located 200 kilometers (125 mi) east of the Rose Run 4 reservoir. D = Dome and RD = Regional Dip.

Table 5. Cost of CCS for a source located 200 kilometers (125 mi) east of the Rose Run 4 reservoir.

Dome Structure														
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost New Build	Rose Run 4				Mt Simon 9				Mt Simon 1			
			Trans 200 km	Storage	Trans+Stor	CCS	Trans583 km	Storage	Trans+Stor	CCS	Trans 982 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	Structure too small				11.11	13.19	24.30	**80.40**	20.02	5.32	25.34	**81.44**
581/482	3.6	57.80					11.55	13.43	24.98	**82.78**	19.37	5.66	25.03	**82.83**
482/400	3.0	60.20					12.72	13.63	26.35	**86.55**	21.46	5.93	27.39	**87.59**
362/300	2.2	64.30	5.39	40.93	46.32	110.62	16.11	14.26	30.37	**94.67**	26.94	6.81	33.75	98.05
241/200	1.5	70.60	7.49	41.33	48.82	119.42	21.49	15.40	36.89	**107.49**	38.29	8.34	46.63	117.23
121/100	0.7	83.40	13.73	46.76	60.49	143.89	39.82	19.21	59.03	**142.43**	66.72	13.93	80.65	164.05
Regional Dip Structure														
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost New Build	Rose Run 4				Mt Simon 9				Mt Simon 1			
			Trans 200 km	Storage	Trans+Stor	CCS	Trans583 km	Storage	Trans+Stor	CCS	Trans 982 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	3.96	83.91	87.87	143.97	11.11	27.60	38.71	94.81	20.02	8.20	28.22	**84.32**
581/482	3.6	57.80	4.01	83.74	87.75	145.55	11.55	27.94	39.49	97.29	19.37	8.49	27.86	**85.66**
482/400	3.0	60.20	4.31	83.76	88.07	148.27	12.72	28.09	40.81	101.01	21.46	8.82	30.28	**90.48**
362/300	2.2	64.30	5.39	84.53	89.92	154.22	16.11	28.73	44.84	109.14	26.94	9.82	36.76	**101.06**
241/200	1.5	70.60	7.49	85.18	92.67	163.27	21.49	30.20	51.69	122.29	38.29	11.41	49.70	**120.30**
121/100	0.7	83.40	13.73	91.58	105.31	188.71	39.82	34.69	74.51	**157.91**	66.72	16.86	83.58	166.98

6.2.2. Rose Run 3 Reservoir

While permeability, porosity, and storage coefficients are the same for both the Rose Run 4 and Rose Run 3 reservoirs, the Rose Run 3 reservoir is 99 meters (325 ft) thicker and 2,286 meters (7,500 ft) deeper than the Rose Run 4 reservoir (Table 1). While a thicker reservoir reduces the areal extent of the CO_2 plume, in turn reducing overall monitoring, verification, and accounting (MVA) costs, a deeper formation leads to increased drilling costs. In this case, the MVA costs are reduced enough to offset higher drilling costs and result in lower injection and storage costs. Storage costs for the Rose Run 3 reservoir are 40 to 46 percent lower than storage costs for the Rose Run 4 reservoir.

Table 6 lists the capture cost, storage cost, transportation cost, and overall CCS cost in the Rose Run 3, Mt Simon 1, and Mt Simon 9 reservoirs (dome and regional dip) at all rates of capture for a source located 100 kilometers (62 mi) east of the Rose Run 3 reservoir. In the dome structural setting, the low-cost reservoir for all rates of CO_2 capture is the Rose Run 3. The Rose Run 3 dome structural setting also has sufficient areal extent to accommodate the storage projects modeled (Table 2). While the cost of storage in the Mt Simon 9 and the Mt Simon 1 reservoirs is lower, it is not low enough to offset the additional cost of transportation (Table 6). The Mt Simon 9 reservoir is 578 kilometers (359 mi) from the source, increasing transportation costs by a factor of 5 to 6 across the range of capture rates modeled. The Mt Simon 1 reservoir is 977 kilometers (607 mi) from the source, increasing transportation costs by a factor of 9 to 10 across the range of capture rates modeled.

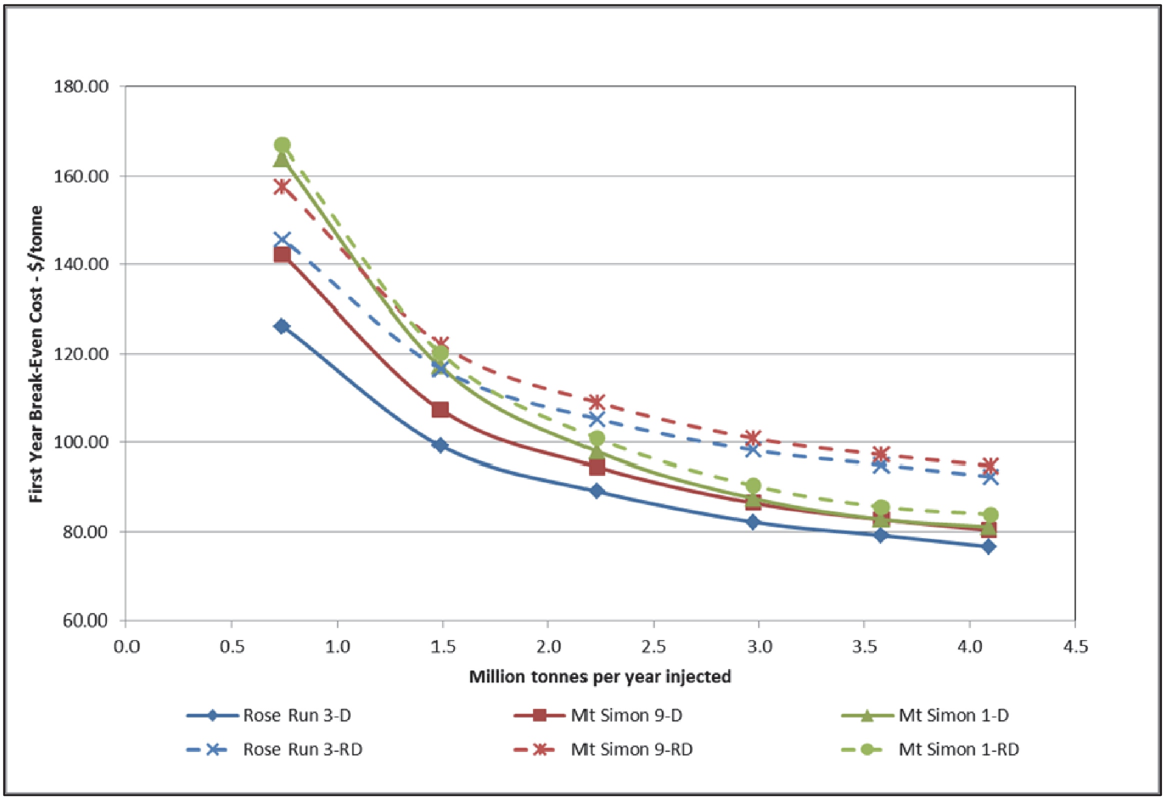

Figure 6. CCS cost for source located 100 kilometers (62 mi) east of the Rose Run 3 reservoir. D = Dome and RD = Regional Dip.

Table 6. Capture, transportation, storage and total CCS cost for source located 100 kilometers (62 mi) east of Rose Run 3 reservoir.

Dome Structure														
		Capture Cost	Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	New Build	Trans 100 km	Storage	Trans+Stor	CCS	Trans 578 km	Storage	Trans+Stor	CCS	Trans 977 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	1.83	18.65	20.48	**76.58**	11.04	13.19	24.23	80.33	19.58	5.32	24.90	81.00
581/482	3.6	57.80	2.03	19.29	21.32	**79.12**	11.47	13.43	24.90	82.70	19.29	5.66	24.95	82.75
482/400	3.0	60.20	2.01	19.95	21.96	**82.16**	12.63	13.63	26.26	86.46	21.37	5.93	27.30	87.50
362/300	2.2	64.30	2.74	22.03	24.77	**89.07**	15.98	14.26	30.24	94.54	26.81	6.81	33.62	97.92
241/200	1.5	70.60	3.63	24.96	28.59	**99.19**	21.34	15.40	36.74	107.34	38.10	8.34	46.44	117.04
121/100	0.7	83.40	7.00	35.80	42.80	**126.20**	39.50	19.21	58.71	142.11	66.40	13.93	80.33	163.73
Regional Dip Structure														
		Capture Cost	Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	New Build	Trans 100 km	Storage	Trans+Stor	CCS	Trans 578 km	Storage	Trans+Stor	CCS	Trans 977 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	1.83	34.41	36.24	92.34	11.04	27.60	38.64	94.74	19.58	8.20	27.78	**83.88**
581/482	3.6	57.80	2.03	35.16	37.19	94.99	11.47	27.94	39.41	97.21	19.29	8.49	27.78	**85.58**
482/400	3.0	60.20	2.01	36.04	38.05	98.25	12.63	28.09	40.72	100.92	21.37	8.82	30.19	**90.39**
362/300	2.2	64.30	2.74	38.21	40.95	105.25	15.98	28.73	44.71	109.01	26.81	9.82	36.63	**100.93**
241/200	1.5	70.60	3.63	42.34	45.97	**116.57**	21.34	30.20	51.54	122.14	38.10	11.41	49.51	120.11
121/100	0.7	83.40	7.00	55.25	62.25	**145.65**	39.50	34.69	74.19	157.59	66.40	16.86	83.26	166.66

Figure 7. CCS cost for source located 200 kilometers (125 mi) east of Rose Run 3 reservoir. D = Dome and RD = Regional Dip.

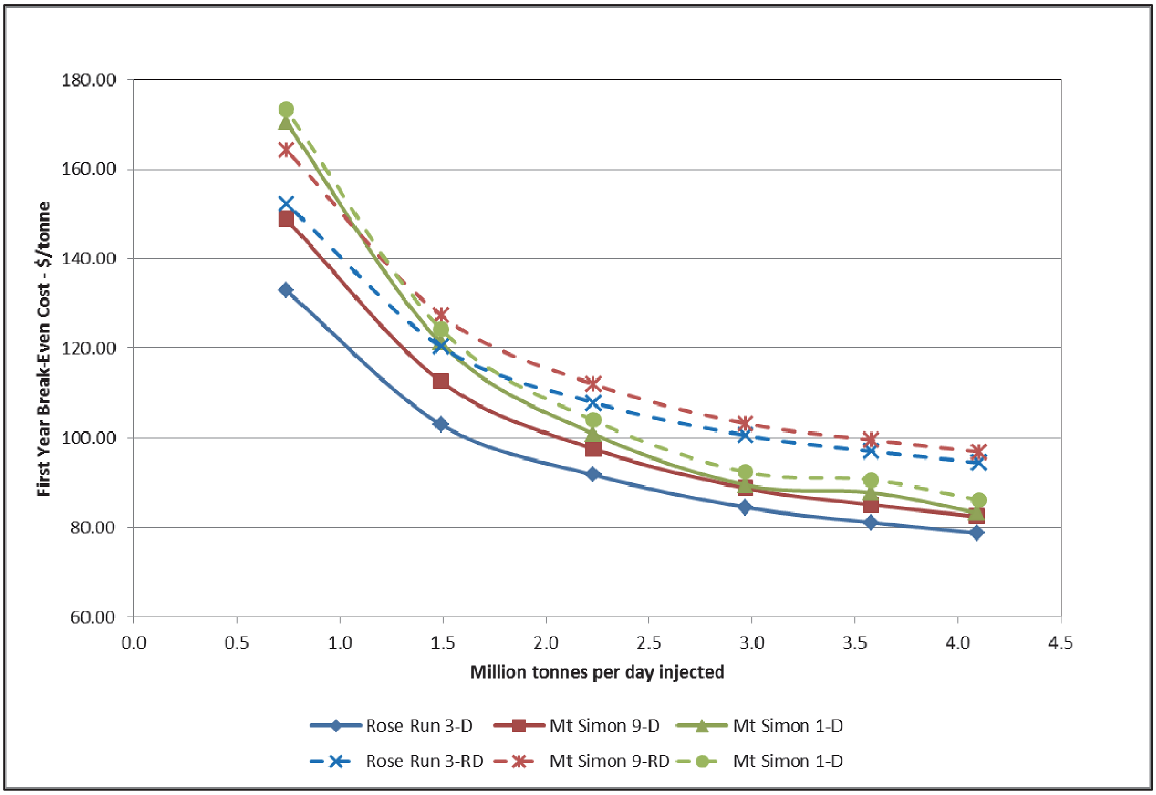

Table 7. Capture, transportation, storage, and total CCS costs for a source located 200 kilometers (125 mi) east of the Rose Run 3 reservoir.

Dome Structure														
		Capture Cost	Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW	Captured CO2 Mt/y	New Build	Trans 200 km	Storage	Trans+Stor	CCS	Trans 679 km	Storage	Trans+Stor	CCS	Trans 1,078 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	3.96	18.65	22.61	**78.71**	13.18	13.19	26.37	82.47	21.85	5.32	27.17	83.27
581/482	3.6	57.80	4.01	19.29	23.30	**81.10**	13.81	13.43	27.24	85.04	24.33	5.66	29.99	87.79
482/400	3.0	60.20	4.31	19.95	24.26	**84.46**	14.93	13.63	28.56	88.76	23.32	5.93	29.25	89.45
362/300	2.2	64.30	5.39	22.03	27.42	**91.72**	19.00	14.26	33.26	97.56	29.83	6.81	36.64	100.94
241/200	1.5	70.60	7.49	24.96	32.45	**103.05**	26.65	15.40	42.05	112.65	42.36	8.34	50.70	121.30
121/100	0.7	83.40	13.73	35.80	49.53	**132.93**	46.24	19.21	65.45	148.85	73.14	13.93	87.07	170.47
Regional Dip Structure														
		Capture Cost	Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW	Captured CO2 Mt/y	New Build	Trans 200 km	Storage	Trans+Stor	CCS	Trans 679 km	Storage	Trans+Stor	CCS	Trans 1,078 km	Storage	Trans+Stor	CCS
		$/tonne	$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	3.96	34.41	38.37	94.47	13.18	27.60	40.78	96.88	21.85	8.20	30.05	**86.15**
581/482	3.6	57.80	4.01	35.16	39.17	96.97	13.81	27.94	41.75	99.55	24.33	8.49	32.82	**90.62**
482/400	3.0	60.20	4.31	36.04	40.35	100.55	14.93	28.09	43.02	103.22	23.32	8.82	32.14	**92.34**
362/300	2.2	64.30	5.39	38.21	43.60	107.90	19.00	28.73	47.73	112.03	29.83	9.82	39.65	**103.95**
241/200	1.5	70.60	7.49	42.34	49.83	**120.43**	26.65	30.20	56.85	127.45	42.36	11.41	53.77	124.37
121/100	0.7	83.40	13.73	55.25	68.98	**152.38**	46.24	34.69	80.93	164.33	73.14	16.86	90.00	173.40

In the regional dip structural setting, the Rose Run 3 reservoir is still the low-cost option at capture rates of 0.7 Mt and 1.5 Mt of CO_2 per year. However, at capture rates of 2.2 Mt of CO_2 per year and above, transporting the captured CO_2 to the Mt Simon 1 reservoir becomes the low-cost option. With a lower storage coefficient, porosity and reservoir thickness become more important. The thicker reservoir gives the Mt Simon 1 a distinct advantage over both the Rose Run 3 and Mt Simon 9 (Table 1). A longer transportation distance to the Mt Simon 1 reservoir of 977 kilometers (607 mi) is economic.

Table 7 shows that the same results hold true for both structural settings when the source is located 200 kilometers (125 mi) east of the Rose Run 3 reservoir, which only further increases the distance to the Mt Simon 9 and Mt Simon 1 reservoirs. Figures 6 and 7 display the cost trends for each of the reservoirs and both structural settings at the respective modeled distances from the Rose Run 3 reservoir. Locating the source west of the Rose Run 3 presents some interesting cost scenarios. The source can choose to go east to utilize Rose Run 3 reservoir or go west to utilize either the Mt Simon 9 or Mt Simon 1 reservoirs. This location decreases the transportation distance to the Mt Simon 9 and Mt Simon 1 reservoirs, lowering transportation costs and, in turn, the combined transportation and storage costs. The Rose Run 4, which is northwest of the Rose Run 3 storage site (Figure 1), is closer to the source in this scenario but storage here is uneconomic at the distance to be covered by a pipeline due to the high cost of storage at the Rose Run 4 reservoir.

Table 8 lists the capture cost, storage cost, transportation cost, and overall CCS cost in the Rose Run 3, Mt Simon 1, and Mt Simon 9 reservoirs (dome and regional dip) at all rates of capture for a source located 100 kilometers (62 mi) west of the Rose Run 3 reservoir. In the dome structural setting, the source has multiple options for low-cost storage across all rates of capture as overall CCS costs are similar for multiple reservoirs. The Mt Simon 1 reservoir provides the low-cost combination of CCS costs at the capture rate of 4.1 Mt of CO_2 per year, the Mt Simon 9 at 3.6 Mt and 2.2 Mt, and the Rose Run 3 at 3.0 Mt, 1.5 Mt, and 0.7 Mt. However, the source has a choice between the Mt Simon 1, Mt Simon 9, and Rose Run 3 reservoirs for storage at capture rates of 3.0 Mt to 4.1 Mt per year since the overall CCS cost difference between these three reservoirs is less and \$1.00 per tonne of CO_2. Considering that the source is between the Rose Run 3 and Mt Simon 9 reservoirs, this \$1.00 per tonne CO_2 variance covers a change in distance of up to 678 kilometers (421 mi), which is the difference between building a pipeline east to the Rose Run 3 reservoir or west to the Mt Simon 1 reservoir. Similarly, for capture rates of 1.5 Mt and 2.2 Mt per year, the source can choose between the Mt Simon 9 and Rose Run 3 reservoirs, while at the lowest capture rate of 0.7 Mt of CO_2 per year the Rose Run 3 reservoir alone provides the low-cost CCS.

Results for the regional dip structural setting show that the Mt Simon 1 reservoir provides the lowest cost of overall CCS for capture rates of 4.1 Mt to 1.5 Mt of CO_2 captured per year. Neither the Rose Run 3 nor Mt Simon 9 reservoir can provide storage cheap enough to lower CCS costs within \$1.00 per tonne of CO_2 of the Mt Simon 1 combination. At the lowest CO_2 capture rate of 0.7 Mt, the Mt Simon 9 reservoir provides storage at the lowest overall CCS cost.

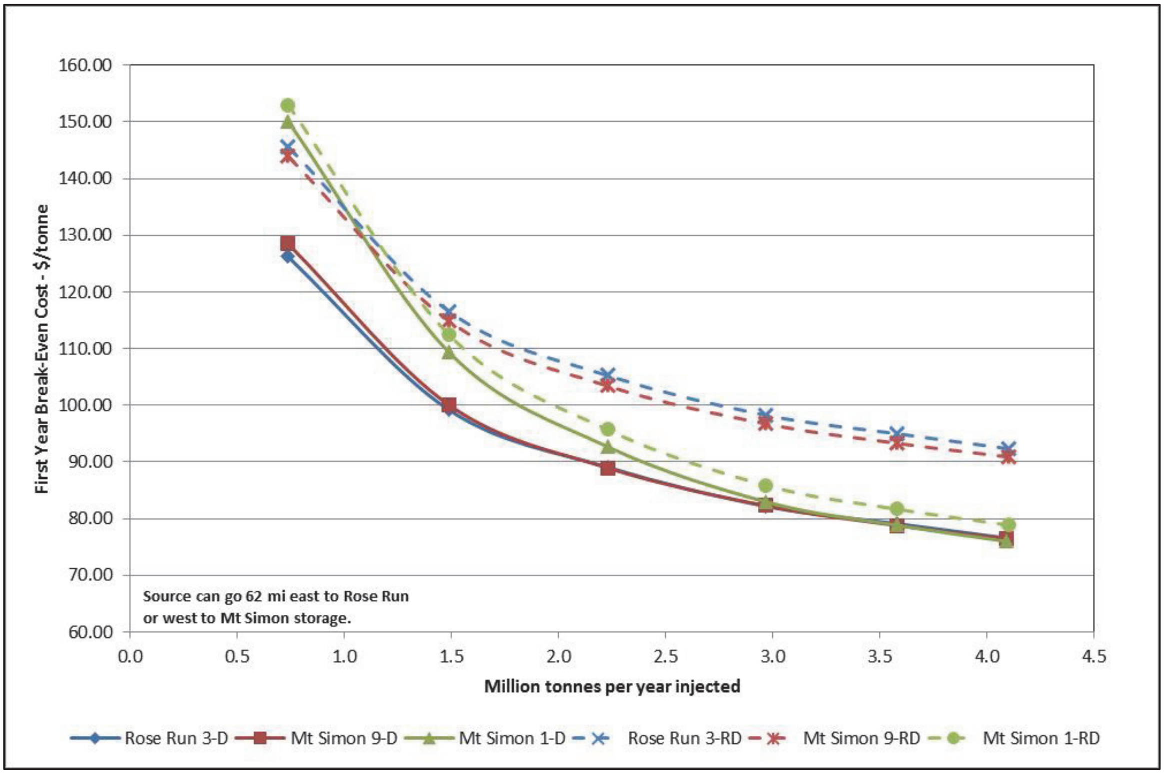

Figure 8. CCS cost for source located 100 kilometers (62 mi) west of the Rose Run 3 reservoir. Source can go east for storage in the Rose Run 3 reservoir for storage or go west to one of the Mt Simon reservoirs. D = Dome and RD = Regional Dip.

Table 8. Capture, transportation, storage, and total CCS costs for source located 100 kilometers (62 mi) west of the Rose Run 3 reservoir. Source can go east for Rose Run 3 storage or west to Mt Simon storage.

Dome Structure														
			Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost New Build $/tonne	Trans 100 km	Storage	Trans+Stor	CCS	Trans 378 km	Storage	Trans+Stor	CCS	Trans 777 km	Storage	Trans+Stor	CCS
			$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	1.83	18.65	20.48	**76.58**	7.17	13.19	20.36	**76.46**	14.56	5.32	19.88	**75.98**
581/482	3.6	57.80	2.03	19.29	21.32	**79.12**	7.56	13.43	20.99	**78.79**	15.38	5.66	21.04	**78.84**
482/400	3.0	60.20	2.01	19.95	21.96	**82.16**	8.43	13.63	22.06	**82.26**	16.82	5.93	22.75	**82.95**
362/300	2.2	64.30	2.74	22.03	24.77	**89.07**	10.39	14.26	24.65	**88.95**	21.58	6.81	28.39	92.69
241/200	1.5	70.60	3.63	24.96	28.59	**99.19**	14.06	15.40	29.46	100.06	30.43	8.34	38.77	109.37
121/100	0.7	83.40	7.00	35.80	42.80	**126.20**	25.87	19.21	45.08	128.48	52.77	13.93	66.70	150.10
Regional Dip Structure														
			Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost $/tonne	Trans 100 km	Storage	Trans+Stor	CCS	Trans 378 km	Storage	Trans+Stor	CCS	Trans 777 km	Storage	Trans+Stor	CCS
			$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	1.83	34.41	36.24	92.34	7.17	27.60	34.77	90.87	14.56	8.20	22.76	**78.86**
581/482	3.6	57.80	2.03	35.16	37.19	94.99	7.56	27.94	35.50	93.30	15.38	8.49	23.87	**81.67**
482/400	3.0	60.20	2.01	36.04	38.05	98.25	8.43	28.09	36.52	96.72	16.82	8.82	25.64	**85.84**
362/300	2.2	64.30	2.74	38.21	40.95	105.25	10.39	28.73	39.12	103.42	21.58	9.82	31.40	**95.70**
241/200	1.5	70.60	3.63	42.34	45.97	116.57	14.06	30.20	44.26	114.86	30.43	11.41	41.84	**112.44**
121/100	0.7	83.40	7.00	55.25	62.25	145.65	25.87	34.69	60.56	**143.96**	52.77	16.86	69.63	153.03

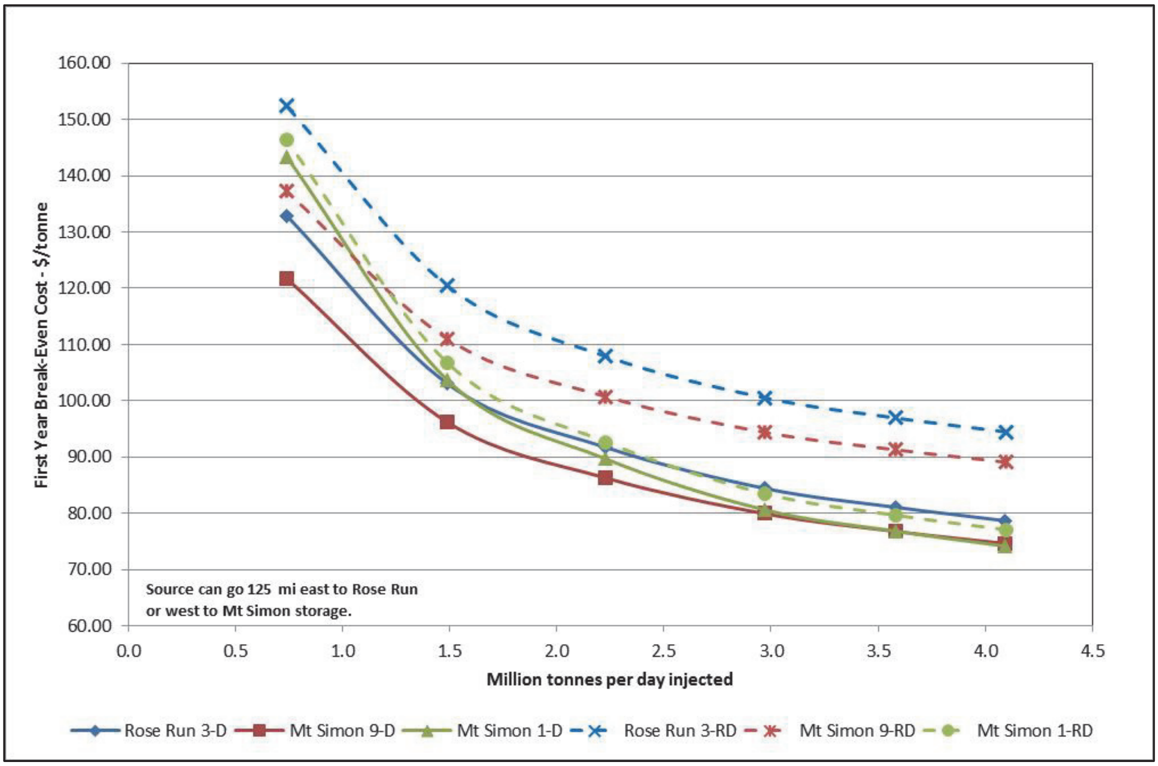

Figure 9. CCS cost for source located 200 kilometers (125 mi) west of the Rose Run 3 reservoir. Source can go east for storage in the Rose Run 3 reservoir for storage or go west to one of the Mt Simon reservoirs. D = Dome and RD = Regional Dip.

Table 9. Capture, transportation, storage, and total CCS costs for source located 200 kilometers (125 mi) west of the Rose Run reservoir. Source can go east for Rose Run 3 storage or west to Mt Simon storage.

Dome Structure			Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost New Build $/tonne	Trans 200 km	Storage	Trans+Stor	CCS	Trans 277 km	Storage	Trans+Stor	CCS	Trans 676 km	Storage	Trans+Stor	CCS
			$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	3.96	18.65	22.61	78.71	5.38	13.19	18.57	**74.67**	12.78	5.32	18.10	**74.20**
581/482	3.6	57.80	4.01	19.29	23.30	81.10	5.58	13.43	19.01	**76.81**	13.40	5.66	19.06	**76.86**
482/400	3.0	60.20	4.31	19.95	24.26	84.46	6.12	13.63	19.75	**79.95**	14.51	5.93	20.44	**80.64**
362/300	2.2	64.30	5.39	22.03	27.42	91.72	7.73	14.26	21.99	**86.29**	18.56	6.81	25.37	89.67
241/200	1.5	70.60	7.49	24.96	32.45	103.05	10.20	15.40	25.60	**96.20**	24.74	8.34	33.08	103.68
121/100	0.7	83.40	13.73	35.80	49.53	132.93	19.13	19.21	38.34	**121.74**	46.03	13.93	59.96	143.36
Regional Dip Structure			Rose Run 3				Mt Simon 9				Mt Simon 1			
Plant MW Gross/Net	Captured CO2 Mt/y	Capture Cost New Build $/tonne	Trans 200 km	Storage	Trans+Stor	CCS	Trans 277 km	Storage	Trans+Stor	CCS	Trans 676 km	Storage	Trans+Stor	CCS
			$/tonne				$/tonne				$/tonne			
663/550	4.1	56.10	3.96	34.41	38.37	94.47	5.38	27.60	32.98	89.08	12.78	8.20	20.98	**77.08**
581/482	3.6	57.80	4.01	35.16	39.17	96.97	5.58	27.94	33.52	91.32	13.40	8.49	21.89	**79.69**
482/400	3.0	60.20	4.31	36.04	40.35	100.55	6.12	28.09	34.21	94.41	14.51	8.82	23.33	**83.53**
362/300	2.2	64.30	5.39	38.21	43.60	107.90	7.73	28.73	36.46	100.76	18.56	9.82	28.38	**92.68**
241/200	1.5	70.60	7.49	42.34	49.83	120.43	10.20	30.20	40.40	111.00	24.74	11.41	36.15	**106.75**
121/100	0.7	83.40	13.73	55.25	68.98	152.38	19.13	34.69	53.82	**137.22**	46.03	16.86	62.89	146.29

Table 9 lists the capture cost, storage cost, transportation cost, and overall CCS cost in the Rose Run 3, Mt Simon 1, and Mt Simon 9 reservoirs (dome and regional dip) at all rates of capture for a source located 200 kilometers (125 mi) west of the Rose Run 3 reservoir. This location further reduces the transportation distance, and cost, to the Mt Simon 9 and Mt Simon 1 reservoirs and increases overall CCS costs by more than \$1.00 per tonne of CO_2 in the Rose Run 3 reservoir. Although the results for the regional dip structural setting are similar to those found in Table 8, the options that were available for low cost storage in the dome structural setting no longer exist. In this case, the Mt Simon 1 reservoir provides storage for low-cost CCS at capture rates of 4.1 Mt CO_2 per year and the Mt Simon 9 is the low-cost site for all other rates of capture. However, at capture rates of 4.1 Mt per year, 3.6 Mt per year, and 3.0 Mt per year, the Mt Simon 1 and Mt Simon 9 CCS cost differences are less than \$1.00 per tonne of CO_2. At the lower rates of 2.2 Mt per year, 1.5 Mt per year, and 0.7 Mt per tonne of CO_2 captured per year, neither the Rose Run 3 nor Mt Simon 1 reservoirs are within the \$1.00 per tonne of CO_2 variance of the Mt Simon 9 reservoir. Figures 8 and 9 display the cost trends for each of the reservoirs and both structural settings at the respective modeled distances from the Rose Run 3 reservoir.

7. Discussion

This simple exercise in modeling CCS costs focused on a single source with a range of possible CO_2 emissions captured and the option to select between three reservoirs for storage. The primary site for the source is a fixed distance from either the Rose Run 3 reservoir or Rose Run 4 reservoir. At each location, the source has the option of selecting either the Mt Simon 9 reservoir or Mt Simon 1 reservoir however, both present a longer distance for transportation. The cost of capture and the cost of storage are fixed at each rate of capture but transportation costs vary with the source location. It is the combined cost of storage and transportation that determine which reservoir provides the lowest CCS cost combination.

For the dome structural setting, a source located east of the Rose Run 3 reservoir, either 100 (Table 6) or 200 kilometers (Table 7), will select the Rose Run 3 reservoir for low cost storage. Changing the location of the source from 100 kilometers east of the Rose Run 3 reservoir to 100 kilometers west of the Rose Run 3 reservoir (Table 8) increases the options for low cost storage from one to three reservoirs for the source. This 200 km shift in the location of the source lowers transportation costs enough for the source to consider storage in either the Mt Simon 1 or the Mt Simon 9 in addition to the Rose Run 3. When the source is located 200 kilometers west of the Rose Run 3 reservoir (Table 9), the lowest CCS costs are at the Mt Simon 1 or 9 reservoirs since the transportation cost to the Rose Run 3 reservoir increases making the combined transportation and storage cost for that reservoir higher than either of the Mt Simon options (Table 9).

The reduction in the storage coefficient for the regional dip structural setting has a significant impact on storage capacity and cost. A source located east of the Rose Run 3 reservoir, either 100 (Table 6) or 200 kilometers (Table 7), will choose the furthest reservoir, the Mt Simon 1, for storage at capture rates ranging from 4.1 Mt to 2.2 Mt. The Rose Run 3 reservoir provides low cost storage at the lower capture rates of 1.5 Mt and 0.7 Mt. Place the source west of the Rose Run 3 reservoir by 100 or 200 kilometers (Table 8 and 9) and it will transport its captured CO_2 to the Mt Simon 1 reservoir for capture rates of 4.1 Mt to 1.5 Mt per year. For the lowest rate of capture modeled, 0.7 Mt per year, the source will choose the Mt Simon 9 reservoir. In the regional dip structural setting, a thick reservoir section is needed to compensate for the lower storage coefficient, providing the Mt Simon 1 reservoir a distinct advantage over either the Mt Simon 9 or Rose Run 3 reservoirs. It also helps that the Mt Simon 1 is significantly shallower than the Rose Run 3, reducing drilling and associated MVA costs. The Mt Simon 9 reservoir has a similar advantage over the Rose Run 3 reservoir.

The quality of the Rose Run 4 reservoir does not provide for cost effective storage for the transportation distances modeled in this analysis. It is even cheaper to transport captured CO_2 offsite than to store it in a Rose Run 4 reservoir onsite. In the dome structural setting, the Mt Simon 9 reservoir provides low-cost storage at all rates of capture for a source located 100 or 200 kilometers east of the Rose Run 4 reservoir. The Mt Simon 1 reservoir provides an alternate location at higher rates of capture. Only at the lowest capture rate of 0.7 Mt of CO_2 per year in a dome structural setting was the Rose Run 4 reservoir close to the cost of storage in the Mt Simon 9. In a regional dip structural setting, cost of storage in the Mt Simon 1 reservoir justifies the higher transportation cost to cover the longer distance. At the lowest rate of capture, 0.7 Mt per year, the Mt Simon 9 is the cost effective option for storage.

Although not specifically modeled, at a distance of 100 or 200 kilometers, a source will choose the Rose Run 3 reservoir over the Rose Run 4 for all scenarios modeled, dome or regional dip structural setting. In both structural settings modeled, the cost of storage in the Rose Run 3 reservoir is about half of that for the Rose Run 4 reservoir.

The trade-off between transport distance and cost-effective CCS changes with a change in the mass of CO_2 captured and the need for suitable low cost storage. This is due to higher unit costs with lower rates of capture or economies of scale for both storage and transportation. The Mt Simon 1 reservoir does not provide cost effective storage at the lowest rates of capture because it is too far away and the transportation cost is too high. When the source is located east of the Rose Run 3 reservoir in a dome structural setting, the source will select this reservoir instead of either Mt Simon reservoir because the transportation costs over the longer distance exceed the advantage provided by lower storage costs. The unit cost of storage for the Rose Run 4 reservoir is high enough to make transportation to either the Mt Simon 1 reservoir or Mt Simon 9 reservoir cost effective.

The lowest cost for transportation, \$1.83 per tonne, is moving 4.1 Mt per year 100 kilometers. This rate of capture costs \$56.10 per tonne. Utilizing a Rose Run 3 dome structure for storage at \$18.65 per tonne gives an overall CCS costs are \$76.58 per tonne. If the source is 100 kilometers east of the Rose Run 3 reservoir the distance to the Mt Simon 1 reservoir is 977 kilometers (607 mi). Transportation cost to the Mt Simon 1 reservoir is \$19.58 per tonne, storage cost is \$5.02 per tonne and overall CCS cost is \$80.70 per tonne. If instead the source is 100 kilometers west of the Rose Run 3 reservoir, the Mt Simon 1 reservoir is only 777 kilometers (483 mi) away with transportation costs of \$14.56 per tonne. With overall CCS costs of \$75.98 per tonne, the cost of utilizing the Mt Simon 1 reservoir is now slightly cheaper than that for the Rose Run 3 reservoir.

Selecting a reservoir with regional dip structural setting, storage costs for the Mt Simon 1 increase to \$8.20 per tonne while costs to store in the Rose Run 3 increase to \$34.41 per tonne. For a source 100 kilometers east of the Rose Run 3 reservoir, it is cheaper to utilize the Mt Simon 1 at a distance of 977 kilometers (607 mi) with a CCS cost of \$83.88 per tonne than to utilize the Rose Run 3 only 100 kilometers away with a CCS cost of \$92.34. The advantage for the Mt Simon 1 reservoir is that it is twice the thickness of the Rose Run 3 with better porosity and about 3,000 meters shallower.

Selecting a reservoir that will meet the needs of the source is critical for cost effective CCS. Adequate storage capacity within a reasonable areal extent is important for keeping costs down. This study did not place any restrictions on the areal extent of the CO_2 plume or its corresponding uncertainty boundary. It will be up to the owner/operator of a CO_2 storage site to secure leases over an area of sufficient areal extent, capable of accommodating the captured CO_2 from the particular source. Based on the data in the FE/NETL CO_2 Saline Storage Cost Model, only one reservoir in this study, the Mt Simon 1, has the potential to store all of the captured CO_2 within the 259 square kilometer (100 mi_2) limit discussed earlier at all rates of capture. The Mt Simon 1 has the smallest footprint of the reservoirs modeled. Use of the Mt Simon 9 and Rose Run 3 might require the development of two or more storage reservoirs to accommodate all captured CO_2 over the assumed operational lifetime of 30 years. Consideration of multiple storage reservoirs is not unusual. In their base case scenario modeling CO_2 storage costs, IEAGHG concluded that the source they modeled would need three storage reservoirs to accommodate injection of 5 Mt of CO_2 per year over 40 years [6].

8. Conclusions

Reservoir quality is critical for cost effective storage of captured CO_2. Adequate storage requires reservoir volume, a thick, porous formation with good storage efficiency for CO_2 over some areal extent. However, high quality reservoirs might not be located in proximity to all sources that require storage for their captured CO_2. This study has shown that there are indeed tradeoffs between reservoir quality and reservoir proximity when the total cost of CO_2 capture, transport, and storage is considered. In this modeling exercise, in a regional dip structural setting, the Mt Simon 1 reservoir provides storage at the lowest overall CCS cost at capture rates of 2.2 Mt of CO_2 per year and above. The Mt Simon 9 reservoir provides storage at the lowest overall CCS cost at the lower capture rates. It is cost effective to transport the captured CO_2 a longer distance for suitable storage. Structural closure, represented as domes and anticlines in the FE/NETL CO_2 Saline Storage Cost Model, with higher storage efficiencies provide opportunity for storage within the Rose Run 3 reservoir when the source is located to the east. When the source is placed between the Rose Run 3 and Mt Simon 9 reservoirs, both are cost competitive with the Mt Simon 1 reservoir.

The modeling results discussed in this study reflect the data posted in the FE/NETL CO_2 Saline Storage Cost Model v2.0 geologic database. This model calculates the cost of injecting CO_2 over the entire height of the formation. This will not be the case for actual storage reservoirs but this study still highlights the importance of having a thick interval of reservoir rock with very good porosity to provide sufficient storage capacity within a reasonable areal extent.

Early deployments of carbon capture and storage technologies will explore for structural traps with the potential for higher storage efficiencies. However, they may settle for economic regional dip structures. FutureGen 2.0 is utilizing the Mt Simon in a regional dip setting. In the Appalachian Basin, early movers in CCS deployment, especially smaller sources with lower costs of capture, may secure structural settings with closure within nearby reservoirs for storage of their captured CO_2. Larger sources or those that deploy later might find that they have to develop storage projects, either with structural closure or a regional dip, out of state or in the neighboring sedimentary basin to minimize the total cost of CCS.

This study provides a methodology for further analysis of the overall cost of CO_2 capture, transport, and storage. This study focuses on one type of technology for power plants, supercritical pulverized coal. The cost of capture increased with lower rates of emissions. Other types of sources should be modeled for overall CCS costs. High purity sources, for example, provide an opportunity for lower cost of capture at lower rates of emissions. The location of the sources and reservoirs in this study are merely representative to keep the initial analyses simple. With the methodology in place, future studies can be conducted for other types of sources in different basins and modeling different reservoirs. The use of trunk pipelines providing transportation for multiple sources and distribution lines to multiple storage sites should also be considered in future modeling efforts.

9. References

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